The Iron, Magnesium, and Calcium Distribution in Coexisting Olivines and Rhombic Pyroxenes of Chondrites

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Abstract. Iron, magnesium, and calcium in olivines and pyroxenes of 95 chondritic meteorites were analyzed with an electron microprobe. Of these, 86 were 'ordinary' chondrites, each having constant iron-magnesium ratios in olivine and pyroxene. Between different meteorites these ratios vary within three narrow ranges which reflect the H- and L-group chondrites, as well as a third group, designated the LL group. The ratio of iron in olivine to that in coexisting pyroxene is nearly constant ($\sim$1.1), particularly within the groups mentioned. A classification of stony meteorites based on the amount of iron in silicates and metal is proposed. It is shown that the iron content in the silicates is not related to the degree of metamorphism (recrystallization), and that therefore, the composition of the silicates was essentially established when the chondrules were formed. The ferrous iron also is not strictly related to the amount of metallic nickel-iron. Thus Prior's rule is not valid in its original sense, although it can be applied qualitatively when comparing the different groups of chondrites. The coexisting olivines and pyroxenes may not be in equilibrium in spite of their constant composition and the constant ratio between their iron contents. Furthermore, the metallic nickel-iron seems to have originated in the same melt as did the silicates.

Introduction

It has been previously observed that chondrites show varying degrees in their oxidation state. For example, enstatite chondrites are almost free of divalent and trivalent iron[1] and must have been formed under strongly reducing conditions. In carbonaceous chondrites, however, the iron is almost completely oxidized to the divalent and trivalent states, and only minor amounts of metallic nickel-iron occur in them. The ordinary chondrites show a state of oxidation somewhere between these extremes, containing varying but considerable amounts of metallic nickel-iron together with divalent iron compounds. *Prior* [1916a, 1920] attempted, in his classical papers, to correlate the mineralogical and chemical composition of the silicate minerals and the metallic nickel-iron in chondrites with the degree of oxidation. His conclusion, based mainly on bulk chemical analyses, was

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[1] Electron microprobe analyses of silicates from the enstatite chondrites St. Marks, Indarch, and Hvittis show small amounts of divalent iron.

'the less the amount of nickel-iron in chondritic stones, the richer it is in nickel and the richer in iron are the magnesium silicates.' This correlation, known since then as Prior's rule, has been accepted by most subsequent investigators and has been supported by later authors such as *Brown and Patterson* [1947a, b; 1948] and, more recently, *Ringwood* [1961]. It has been questioned by *Urey and Craig* [1953], however, on the basis of their extensive study of 'superior' chemical analyses of chondrites available in the literature. Whether the iron content in the iron-magnesium silicates of chondrites can serve as a quantitative measure of the degree of oxidation is not yet certain. A comprehensive discussion of this problem, partly based on the data presented below, will be published by *Suess* [1964].

Another crucial problem for any hypothesis on the origin of chondrites is the existence of certain distinct groups among the chondritic meteorites. Urey and Craig demonstrated in 1953 the existence of two groups of chondrites, one having a low total iron content (22.33 weight per cent), the other a high content (28.58 weight

per cent). These they designated the L group and the H group. The existence of these two groups can also be deduced from the metallic nickel-iron content and from the specific gravity [*Keil*, 1962a, b]. At present, it is not clear whether the two groups should be ascribed to two different parent bodies or two groups of bodies, as Urey and Craig suggested in 1953, or whether the L group could have been derived from the H group by loss of metallic nickel-iron, accompanied by recrystallization under slightly oxidizing conditions [*Ringwood*, 1961].

In the past years many hypotheses concerning the origin of chondrules and chondritic meteorites have been proposed (for a summary, see *Mason* [1962b]). Most investigators agree that chondrules originated as molten droplets which later accumulated into larger bodies. The structure of the chondrules and chondrites presumably has later been influenced by recrystallization and metamorphic processes [e.g., *Sorby*, 1877; *Merrill*, 1921; *Kvasha*, 1958]. Students of meteorites do not yet wholly agree on whether the basic difference in oxidation state and in composition of the phases in chondrules and chondrites is due to varying conditions during the chondrule formation, as *Ringwood* [1961] proposed, or due to later recrystallization and metamorphism, accompanied by a diffusion of iron in solid state from magnetite distributed throughout the matrix of the primitive chondrite into olivine and pyroxene inside the chondrules, producing the distributions now observed [*Wood*, 1962a, b; 1963a, b].

The present study was undertaken in the hope that more accurate data than have formerly been available on the composition of coexisting minerals in chondrites could give some clues to the problems outlined above. For this purpose the iron, magnesium, and calcium contents of coexisting olivine (isomorphous series of Mg_2SiO_4-Fe_2SiO_4) and rhombic pyroxene (isomorphous series of $MgSiO_3$-$FeSiO_3$) in a large number of different chondrites have been measured.

METHOD

In the past, the composition of coexisting olivines and rhombic pyroxenes in chondrites has been calculated from bulk chemical analyses (a process not always reliable [*Wiik*, 1956]), has been determined by analyzing mechanically separated pure mineral phases, has been measured optically, or has been obtained by X-ray diffraction. The chemical analysis of separated phases is rather restricted because of the problems involved in clean separation of these phases from the complex intergrowths in chondrites. Furthermore, the chemical analysis of separated phases gives the bulk composition of a large number of individual crystals of the same material without taking into account the possible variability in composition from grain to grain or the zonal structure. Nor can chemical analysis enable measurement of the composition of the occasionally occurring fine exsolution lamellas in pyroxenes, which differ in composition from the host pyroxene. Lastly, the error involved in the optical as well as the X-ray diffraction techniques is relatively high, amounting to about 5 to 10 per cent of the fayalite contents.

In comparison with those methods, the electron microprobe has proved to be a particularly useful tool for solving the problems mentioned. With the use of proper standards, the precision of the individual results is as good as ±0.1 per cent Fe and ±0.2 per cent Mg in olivine and rhombic pyroxene and the accuracy is of the order of ±0.3 per cent Fe and Mg. Furthermore, the method is nondestructive and permits analysis of single grains, as small as a few microns in size, as well as of thin exsolution lamellas and crystals with zonal structure.

The measurements were made on polished sections of a diameter of 1.5 to 2.5 cm which had been coated with a layer of carbon a few hundred angstroms thick. The composition of olivines and rhombic pyroxenes in 95 chondrites was determined by using a modified ARL (Applied Research Laboratories, Glendale, California) electron microprobe X-ray analyzer. This instrument is equipped with three dispersive monochromators which enable the measurement of three different elements (three different wavelengths) at the same time. Therefore, it was possible to measure Fe, Mg, and Ca simultaneously and in exactly the same position on the sample. At least four analyses, 3 to 5 microns apart, were usually made on each grain. Some 20 to 30 olivine and rhombic pyroxene grains from each meteorite were measured. From each of the minerals with varying composition or zonal structure as many as several hundred grains were analyzed. The composition of the
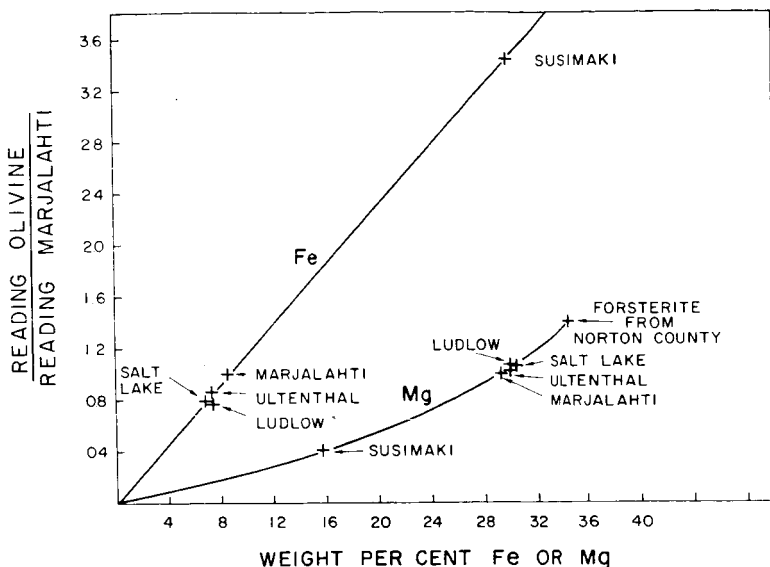
Fig. 1.   Calibration curves for Fe and Mg in olivine.

crystals was then ascertained by moving the sample in steps from 4 to 20 microns under the fixed electron beam, thus covering the grain with rows of analyses.

For the quantitative analysis of Fe and Mg in olivines, five chemically analyzed olivines and a pure forsterite (<0.1 weight per cent Fe) from the Norton County achondrite [*Keil and Fredriksson*, 1963*b*] were used as standards, thus covering the range from pure Mg_2SiO_4 to 45.3 mole per cent Fe_2SiO_4. From the chemical analyses of these olivines (cf. *Ross et al.* [1954] on olivines from Ludlow, California, and from Salt Lake Crater, Oahu, Hawaiian Islands; and also *Yoder and Sahama* [1957] on olivines from Susimaki, Finland, from Ultenthal, Tyrol, Austria, and from the Marjalahti, Finland, meteorite) the Fe and Mg values were calculated, the small amount of Fe_2O_3 being ascribed to magnetite inclusions. The chemical composition and the degree of homogeneity of these standards were controlled by using the microprobe to analyze them against pure metallic iron standards. After corrections were made for wavelength shift, detector dead time, background, mass absorption, and atomic number,[2] agree-

ment with the chemical analyses was found to be ±0.3 per cent Fe. With use of the values given by the chemical analysis, Fe and Mg calibration curves were drawn for the olivines (Figure 1), and further values were evaluated graphically. For Fe and Mg in rhombic pyroxenes, calibration curves were calculated theoretically from the olivine curves by applying the proper mass absorption corrections. In order to control the theoretical calibration curves for rhombic pyroxene, three pyroxenes with known composition were measured (two analyses by *Engel et al.* [1964], nos. AC 362-Or and A 104-Or, and pure enstatite (<0.1 per cent Fe) from the Norton County achondrite). The theoretical curves for rhombic pyroxene are shown in Figure 2. The Mg values of all three pyroxenes match the curve well within the precision of the technique. The zero point on the Fe curve is identical with the value of the enstatite from the Norton County achondrite. The Fe value of analysis AC 362-Or matches the theoretical curve closely. The Fe value of analysis A 104-Or differs somewhat, but this value, according to the chemical analyses, is considerably lower than the Fe values of the five other pyroxenes analyzed by *Engel et al.* [1964], which have nearly the same composition with regard to the other elements present. Since, in particular, the Mg values of

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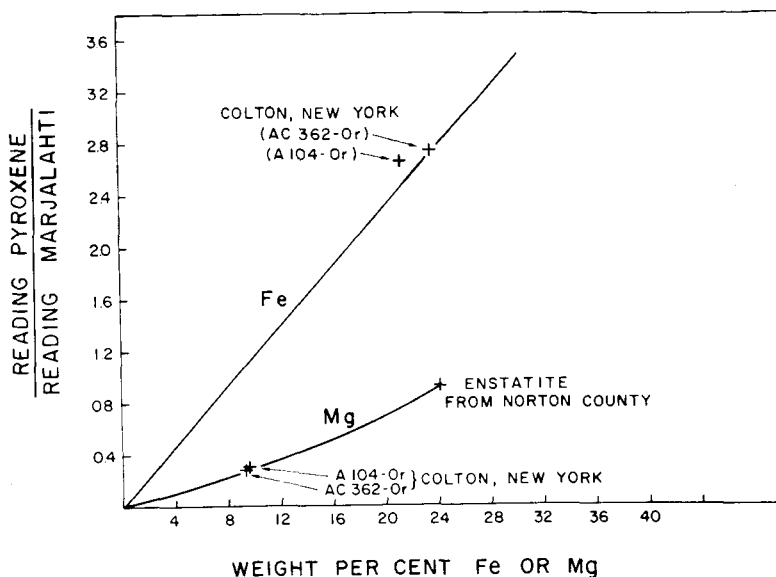[2] The fluorescence correction was found to be negligible.

Fig. 2. Calculated calibration curves for Fe and Mg in rhombic pyroxene.

the two analyses are almost identical, it would seem that the chemically obtained Fe value of sample A 104-Or is somewhat too low, this being the probable reason for the disagreement with the theoretical curve and the analyses of the other rhombic pyroxenes.

The Ca content in rhombic pyroxene was measured by use of chemically analyzed andesine (Ca = 6.9, Al = 14.4, Si = 26.6 weight per cent) and the Ca-rich pyroxene samples A 104-Cl and AC 362-A [Engel et al., 1964] as standards, taking into account the mass absorption corrections. The precision was found to be ±0.1 per cent Ca.

Although the accuracy of the results is chiefly dependent on the quality of the calibration curves discussed above, the precision of the results depends on contamination effects caused by the electron beam on the spot to be analyzed, fluctuations in the electronics, and on the variability in composition of the standards. Since the analyses were always carried out with the same integration time, the contamination effect is negligible. Furthermore, it was found that optical refocusing did not affect the readout. To evaluate the effects of the electronic fluctuations and possible inhomogeneities in the standards, 20 measurements, in positions 3 microns apart, were made on the olivine standard Marjalahti.

The precision was found to be ±0.1 per cent Fe and ±0.2 per cent Mg (Table 1).

RESULTS

The 95 different chondrites examined in the present study are included in alphabetical order in Table 2 showing the metal contents of some of the chondrites. They are numbered in the order of increasing iron in olivine. These numbers facilitate the finding of any one of the examined chondrites in Table 3, in which the analytical results are presented. These results have been recalculated and plotted in several other tables (4, 5, 6) and are shown in Figures 4 to 12 to illustrate the facts discussed below. The results of studies of some other types of meteorites described elsewhere [Fredriksson and Keil, 1963; Keil and Fredriksson, 1963b; Keil et al., 1964] will be discussed so far as they are of significance to the present problems (cf. Figures 13 and 14).

The 95 meteorite samples were randomly selected from several meteorite collections without preference for one or the other type of chondrite. Finds were only included in the study as far as they were believed not to be altered by terrestrial oxidation and weathering. In the tables, the 18 finds are indicated by asterisks.

TABLE 1. Homogeneity of the Mineral Standards and Precision of the Individual Fe and Mg Microprobe Analyses

Example: Olivine standard Marjalahti (Fe = 8.5, Mg = 29.2 weight per cent). Twenty measurements, each position 3 microns apart. Standard deviation: $S_{Fe} = \pm0.07 \sim \pm0.1$, $S_{Mg} = \pm0.17 \sim \pm0.2$.

Position Number	Fe		Mg	
	Measured Intensity Minus Background	Content, weight %	Measured Intensity Minus Background	Content, weight %
1	27.9	8.47	80.4	29.11
2	27.8	8.44	80.5	29.15
3	27.7	8.41	80.0	29.00
4	27.5	8.35	79.8	28.90
5	27.8	8.44	80.0	29.00
6	27.9	8.47	80.9	29.29
7	28.1	8.53	80.4	29.11
8	27.9	8.47	80.0	29.00
9	28.2	8.56	80.9	29.29
10	28.4	8.62	81.3	29.44
11	28.2	8.56	81.2	29.40
12	28.1	8.53	80.7	29.22
13	28.0	8.50	81.1	29.37
14	28.0	8.50	81.2	29.40
15	27.9	8.47	80.0	29.00
16	27.9	8.47	81.2	29.40
17	28.0	8.50	80.6	29.19
18	28.0	8.50	80.8	29.26
19	28.4	8.62	80.5	29.15
20	28.5	8.65	81.4	29.47

The results of the study are stated in the next four sections.

Constancy in composition of olivines and rhombic pyroxenes in any ordinary chondrite. The analyses show that usually in a given meteorite the composition of olivines and rhombic pyroxenes is nearly constant. This fact has already been indicated by the sharp peaks found in X-ray diffraction patterns [*Mason,* 1960, 1963]. According to the microprobe results different olivine and rhombic pyroxene grains of a given chondrite vary less than ±1 per cent Fe and Mg. Figure 3 shows an example. Analyses were made of 84 individual olivine grains from 17 different chondrules of different sizes from the Bjurböle chondrite. The results are plotted in a frequency distribution diagram, illustrating the remarkable uniformity in composition. (This uniformity was also observed for crystals in the matrix.) Table 7 lists the average composition of the 84 olivine grains as well as of 15 rhombic pyroxene grains (from 6 different chondrules)

of the same meteorite.[3] Here again the rather small standard deviations for Fe, Mg, and Ca demonstrate the uniformity in composition of those minerals. (For another example, compare the analyses of 155 individual olivines and 107 individual rhombic pyroxenes of the Pantar chondrite [*Fredriksson and Keil,* 1963].) Such constancy in composition of olivine and rhombic pyroxene holds true for 86 of the 95 chondrites studied (and listed in Table 3). The values given in this table are averages of several analyses of Fe and Mg in 10 to 20 olivines and of Fe, Mg, and Ca in 10 to 20 rhombic pyroxenes. The Ca content in olivine was found to be <0.1 per cent. The Fe/(Fe + Mg) ratios have been calculated from the Fe and Mg averages.

Since the precision of the microprobe measurements is high (±0.1 per cent Fe, ±0.2 per

[3] Much greater variations (olivine, 18 to 29 per cent fayalite; rhombic pyroxene, 18 to 21 per cent orthoferrosilite) reported by *Wood* [1962b] are probably due to inaccurate measurements.

cent Mg), the average values given in Table 3 are characteristic numbers for any given chondrite which might, in connection with the different macroscopical and microscopical appearance of chondrites (color, degree of metamorphism, etc.), serve to identify mislabeled specimens.

Chondrites with olivines and pyroxenes of varying composition. In almost 10 per cent of the chondrites examined, the olivines and pyroxenes vary in composition. Table 8 shows the results of analyses of individual olivines and pyroxenes from these meteorites. Unfortunately, from several of them only very small samples were made available for analysis. Consequently, sampling errors may affect the results; however, more detailed studies of these meteorites on larger samples are planned for the near future. The variability in composition of olivines and pyroxenes in the chondrites listed in Table 8 usually does not exceed 10 to 15 mole per cent $Fe/(Fe + Mg)$. Some of the crystals show zonal structure; others do not. The grains listed in Table 8 that do not show zoning (i.e., that have only one value listed for Fe and one for Mg) may possibly have some zonal structure, which a chance orientation in the section plane might have prevented from being visible and having its variations measured. The chondrite Chainpur, in particular, is an example of a meteorite containing pyroxenes and especially olivines with distinct zonal structure. The difference in the $Fe/(Fe + Mg)$ ratios from the center to the rim is rather large in several crystals, and sometimes it exceeds 10 mole per cent; some of the results are summarized in Figure 13. In the Murray carbonaceous chondrite the individual olivine and pyroxene grains do not exhibit an extensive zoning, but their composition varies over a large range from grain to grain (olivine 0.3 to 91.2; pyroxene 0.4 to 45.4 mole per cent $Fe/(Fe + Mg)$, Figure 14). More detailed descriptions of the several hundred analyses of olivines and pyroxenes from the Chainpur chondrite and the Murray carbonaceous chondrite are given elsewhere [*Keil et al.,* 1964; *Fredriksson and Keil,* 1964].

The relation between iron in coexisting olivine and in rhombic pyroxene of chondrites. It has been pointed out above that for the majority of chondrites studied the composition of olivines as well as that of rhombic pyroxenes is nearly constant from grain to grain of a given mete-

TABLE 2. Alphabetical List of the Chondrites Investigated and Their Metallic Nickel-Iron Contents

No.*	Name	Metallic Nickel-Iron, weight %	Reference
24	Akron†		
61	Albareto	5.23	*Gallitelli* [1939]‡
67	Alfianello	6.79	*Keil* [1962a, b]
7	Allegan	23.05	*Merrill and Stokes* [1900]‡
25	Archie		
68	Arriba†		
15	Assisi		
66	Ausson		
46	Aztec		
40	Bald Mountain		
19	Barbotan		
10	Bath	17.09	*Keil* [1962a, b]
63	Bath Furnace	5.40	*Keil* [1962a, b]
59	Baxter		
26	Beardsley		
27	Beaver Creek	17.68	*Howell et al.* [1894]‡
77	Bjurböle	7.69	*Ramsay and Borgström* [1902]‡
56	Blanket		
73	Brady		
9	Breitscheid	17.71	*Vilcsek* [1959]
70	Bruderheim	8.25	*Duke et al.* [1961]
36	Bushnel†		
34	Butsura	18.47	*Keil* [1962a, b]
51	Calliham†		
57	Chantonnay	6.70	*Keil* [1962a, b]
20	Charsonville		
58	Chateau Renard	6.33	*Keil* [1962a, b]
82	Cherokee Springs		
47	Colby (Wisconsin)		
22	Collescipoli	19.96	*Wahl* [1950a] (Wiik)‡
72	Coon Butte†	9.25	*Mallet* [1906]‡
14	Cosina		
81	Dhurmsala	2.96	*Keil* [1962a, b]
31	Djati-Pengilon	15.75	*Keil* [1962a, b]
21	Dokachi		
33	Ehole		
32	Ekeby	18.66	*Hadding* [1940]‡
49	Eli-Elwah†	6.24	*Keil* [1962a, b]
54	Ergheo	1.56	*Keil* [1962a, b]
28	Estacado†	16.02	*Keil* [1962a, b]
52	Farmington	7.63	*Keil* [1962a, b]
13	Florence		
29	Forest City	21.06	*Kunz* [1890] (Eakins)‡
50	Forksville	7.55	*Merrill* [1927] (Shannon)‡
38	Fukutomi	10.83	*Keil* [1962a, b]
75	Futtehpur		
78	Girgenti	6.21	*Keil* [1962a, b]

TABLE 2.   (Continued)

No.*	Name	Metallic Nickel-Iron, weight %	Reference
79	Harleton	8.51	*Clarke* [1962]
55	Harrisonville†	4.40	*Keil* [1962a, b]
11	Hedeskoga		
16	Hessle	18.98	*Nordenskiold* [1870] (Lindstrom)‡
43	Hökmark		
74	Holbrook	8.33	*Mason and Wiik* [1961c]
42	Homestead	10.99	*Prior* [1918]‡
41	Johnson City†		
64	Kandahar		
86	Kernouve	15.87	*Keil* [1962a, b]
1	Kesen		
65	Knyahinya	4.73	*Keil* [1962a, b]
62	Kuttipuram		
48	Kyushu	6.74	*Keil* [1962a, b]
44	Ladder Creek		
45	L'Aigle	11.65	*Keil* [1962a, b]
5	Menow	16.46	*Keil* [1962a, b]
3	Merua	20.10	*Tipper* [1925]‡
80	Mocs	5.85	*Keil* [1962a, b]
12	Monroe		
39	Mooresfort	7.62	*Keil* [1962a, b]
60	New Concord	8.22	*Keil* [1962a, b]
30	Oakley†	14.63	*Keil* [1962a, b]
83	Oberlin†		
8	Ochansk	20.82	*Wiik* [1956]
23	Pultusk	16.55	*Keil* [1962a, b]
37	Ramsdorf		
2	Richardton		
69	Saint Michel	9.13	*Borgström* [1912]‡
84	Soko-Banja	4.32	*Prior* [1916b]‡
6	Ställdalen	20.79	*Lindstrom* [1877]‡
4	Tabor	16.90	*Keil* [1962a, b]
53	Taiban†		
71	Temple†		
18	Tomhannock Creek†	16.00	*Keil* [1962a, b]
17	Tulia†		
85	Vårvik†§		
76	Walters†		
35	Zhovtnevyi	17.66	*Keil* [1962a, b]

* Number in first column refers to Table 3.

† Meteorites are finds.

‡ 'Superior' chemical analyses according to *Urey and Craig* [1953].

§ This meteorite is listed as Näs by *Prior and Hey* [1953]. This very fresh and unaltered-looking chondrite has been classified as a find; however, a meteorite fall was observed in this area on May 14, 1907. It seems likely that the stone Vårvik, which was found some time thereafter, might have fallen at this particular date.

orite. Only these meteorites have been plotted in the diagrams to be discussed.

In Figure 4 the average mole per cent ratios Fe/(Fe + Mg) in olivine have been plotted versus the Fe/(Fe + Mg) ratios in the coexisting rhombic pyroxenes. It is apparent that the points, each of which represents one chondrite, characteristically cluster into three distinct groups identical with the *Urey and Craig* [1953] L group and H group of chondrites and the Soko-Banja LL group (low iron–low metal) established by *Prior* [1916a].

According to Figure 4, the Fe/(Fe + Mg) ratios of coexisting olivines and rhombic pyroxenes in chondrites are concentrated along an approximately straight line (further illustrated in Figure 5). Only the chondrite Ramsdorf deviates considerably. Although the sample available from it was very small, its pyroxene was found to have the highest calcium content among the chondrites studied, namely 1.1 per cent. X-ray diffraction studies reveal the pyroxene to be monoclinic (Mason, personal communication). (A more detailed study of the Ramsdorf meteorite, with larger samples, is planned for the near future.) The Fe/(Fe + Mg) ratios in olivine are slightly higher than in coexisting rhombic pyroxene, as Figure 4 reveals and as had been previously noted by *Mason* [1962a]. In the diagram in Figure 6 the differences

$$\left(\frac{Fe}{Fe + Mg}\right)_{olivine} - \left(\frac{Fe}{Fe + Mg}\right)_{rh.pyroxene}$$

of the chondrites listed in Table 3 are plotted against the fayalite (Fe_2SiO_4) content of the olivines. This diagram shows that with increasing iron content in the silicates the difference between Fe/(Fe + Mg) in olivine and Fe/(Fe + Mg) in pyroxene also increases.

The LL, L, and H groups of chondrites. The present analyses of olivine and rhombic pyroxene pairs indicate the existence of three distinct groups among chondrites (see Figure 4). It is apparent that the first two groups are identical with the L-group and H-group chondrites of *Urey and Craig* [1953] and with the hypersthene and bronzite chondrites of *Prior* [1920]. The third group is identical with the Soko-Banja group chondrites of *Prior* [1916a]. Table 5 shows that the total iron content in the Soko-Banja group is almost the same as in the L-group chondrites, whereas the metallic nickel-iron con-

TABLE 3. Composition of Coexisting Olivine and Rhombic Pyroxene in 86 Chondrites

No.	Name	Classification in LL, L, and H Groups	Olivine Weight % Fe	Olivine Weight % Mg	Olivine Mole %, Fe Fe + Mg	Rhombic Pyroxene Weight % Fe	Rhombic Pyroxene Weight % Mg	Rhombic Pyroxene Weight % Ca	Rhombic Pyroxene Mole %, Fe Fe + Mg
1	Kesen	H	11.9	27.1	16.1	7.7	19.0	0.40	15.0
2	Richardton	H	12.1	27.3	16.2	7.7	19.4	.27	14.7
3	Merua	H	12.2	26.8	16.5	8.0	18.7	.33	15.7
4	Tabor	H	12.2	26.8	16.5	7.8	18.8	.32	15.3
5	Menow	H	12.9	26.7	17.4	8.0	18.4	.53	15.9
6	Ställdalen	H	13.0	26.3	17.7	8.4	19.2	.38	16.0
7	Allegan	H	13.0	26.6	17.5	8.5	19.4	.37	16.0
8	Ochansk	H	13.0	26.7	17.5	8.2	19.3	.33	15.6
9	Breitscheid	H	13.0	26.8	17.4	8.3	18.8	.40	16.1
10	Bath	H	13.1	26.4	17.8	8.0	18.7	.40	15.7
11	Hedeskoga	H	13.1	26.7	17.6	8.7	18.8	.50	16.8
12	Monroe	H	13.1	26.7	17.6	8.2	19.1	.23	15.8
13	Florence	H	13.1	26.8	17.6	8.3	18.6	.68	16.3
14	Cosina	H	13.1	27.4	17.2	8.3	19.5	.43	15.8
15	Assisi	H	13.2	26.4	17.9	8.6	19.6	.42	16.0
16	Hessle	H	13.2	26.6	17.8	8.2	18.6	.42	16.1
17	Tulia*	H	13.3	26.5	17.9	8.6	19.0	.30	16.5
18	Tomhannock Creek*	H	13.3	26.5	17.9	8.4	18.8	.47	16.3
19	Barbotan	H	13.3	26.5	17.9	8.3	19.0	.39	16.0
20	Charsonville	H	13.3	26.8	17.8	8.7	19.0	.53	16.6
21	Dokachi	H	13.4	26.6	18.0	8.4	18.7	.46	16.4
22	Collescipoli	H	13.4	26.8	17.8	8.6	19.3	.41	16.3
23	Pultusk	H	13.5	26.4	18.2	8.1	19.1	.30	15.6
24	Akron*	H	13.5	26.7	18.0	8.5	18.8	.46	16.5
25	Archie	H	13.5	26.7	18.0	8.5	18.7	.51	16.5
26	Beardsley	H	13.6	26.0	18.6	8.2	18.3	.45	16.3
27	Beaver Creek	H	13.6	26.4	18.3	8.3	19.0	.48	16.0
28	Estacado*	H	13.7	26.4	18.4	8.5	18.6	.35	16.6
29	Forest City	H	13.7	26.6	18.3	8.3	19.0	.40	16.0
30	Oakley*	H	13.7	26.6	18.3	8.7	18.8	.63	16.8
31	Djati-Pengilon	H	13.8	26.2	18.7	8.7	18.7	.40	16.8
32	Ekeby	H	13.9	25.9	18.9	8.6	18.5	.38	16.8
33	Ehole	H	14.0	26.0	19.0	8.6	18.7	.41	16.7
34	Butsura	H	14.0	27.1	18.4	8.8	19.1	.51	16.7
35	Zhovtnevyi	H	14.1	26.2	19.0	8.7	19.0	.37	16.6
36	Bushnel*	H	14.3	25.8	19.4	8.8	18.4	.42	17.2
37	Ramsdorf§	L	15.8	24.9	21.6	9.0	18.0	1.1	17.9
38	Fukutomi	L	15.9	25.1	21.6	10.0	17.7	.34	19.7
39	Mooresfort	L	16.0	24.4	22.2	10.0	17.5	.42	19.9
40	Bald Mountain	L	16.1	24.8	22.0	9.8	17.9	.29	19.3
41	Johnson City	L	16.3	24.2	22.7	9.9	17.2	.54	20.0
42	Homestead†	L	16.3	25.1	22.0	10.3	18.1	.45	19.9
43	Hökmark	L	16.5	24.5	22.7	9.8	17.5	.36	19.6
44	Ladder Creek*	L	16.5	24.6	22.6	10.5	17.2	.65	21.0
45	L'Aigle	L	16.7	24.5	22.9	10.0	17.5	.54	19.9
46	Aztec	L	16.8	24.7	22.9	10.2	17.9	.64	19.9
47	Colby (Wisconsin)	L	17.0	24.2	23.4	10.5	17.4	.30	20.8
48	Kyushu	L	17.0	24.4	23.3	10.4	17.4	.49	20.6
49	Eli-Elwah	L	17.1	24.2	23.5	10.7	17.8	.34	20.7
50	Forksville	L	17.2	23.9	23.9	10.4	17.2	.60	20.8
51	Calliham*	L	17.2	24.0	23.8	10.7	17.2	.62	21.3
52	Farmington	L	17.2	24.0	23.8	10.3	17.4	.57	20.5
53	Taiban*	L	17.2	24.0	23.8	10.8	17.4	.45	21.3
54	Ergheo	L	17.2	24.1	23.7	10.5	17.7	.36	20.5
55	Harrisonville*	L	17.2	24.2	23.6	10.4	17.4	.63	20.6

TABLE 3. (Continued)

No.	Name	Classifi-cation in LL, L, and H Groups	Olivine Weight % Fe	Olivine Weight % Mg	Olivine Mole %, Fe / Fe + Mg	Rhombic Pyroxene Weight % Fe	Rhombic Pyroxene Weight % Mg	Rhombic Pyroxene Weight % Ca	Rhombic Pyroxene Mole %, Fe / Fe + Mg
56	Blanket	L	17.2	24.4	23.5	10.7	17.7	.46	20.8
57	Chantonnay	L	17.2	24.7	23.3	10.4	17.6	.53	20.5
58	Chateau Renard	L	17.3	24.3	23.7	10.3	17.4	.56	20.5
59	Baxter	L	17.3	24.4	23.6	10.7	17.7	.63	20.8
60	New Concord	L	17.3	24.4	23.6	10.4	17.7	.46	20.4
61	Albareto	L	17.4	23.5	24.4	10.6	16.7	.40	21.7
62	Kuttipuram	L	17.4	23.8	24.1	10.5	17.5	.59	20.7
63	Bath Furnace	L	17.4	24.0	24.0	10.4	17.3	.52	20.7
64	Kandahar	L	17.4	24.2	23.8	10.4	17.7	.45	20.4
65	Knyahinya	L	17.4	24.2	23.8	10.6	17.5	.54	20.9
66	Aussun	L	17.4	24.3	23.8	10.6	17.6	.49	20.8
67	Alfianello	L	17.4	24.4	23.7	10.6	17.5	.65	20.9
68	Arriba*	L	17.5	23.9	24.2	10.7	17.2	.43	21.3
69	Saint Michel	L	17.5	24.2	23.9	10.8	17.5	.55	21.2
70	Bruderheim	L	17.5	24.4	23.8	10.9	18.2	.39	20.7
71	Temple*‡	L	17.7	23.8	24.5	10.7	17.5	.47	21.0
72	Coon Butte*	L	17.7	24.0	24.3	10.6	17.6	.54	20.8
73	Brady*	L	17.7	24.3	24.1	10.5	17.9	.65	20.3
74	Holbrook	L	17.8	23.8	24.6	10.5	17.4	.60	20.8
75	Futtehpur	L	17.8	24.2	24.3	10.5	17.4	.51	20.8
76	Walters*	L	17.8	24.0	24.4	10.7	17.4	.52	21.1
77	Bjurböle	L	17.8	23.9	24.5	10.8	17.5	.34	21.2
78	Girgenti	L	17.8	24.2	24.3	10.9	17.7	.47	21.1
79	Harleton	L	17.8	24.4	24.1	10.8	18.0	.55	20.7
80	Mocs	L	17.9	24.1	24.4	10.5	17.4	.46	20.8
81	Dhurmsala	LL	19.0	23.2	26.3	11.2	17.1	.60	22.2
82	Cherokee Springs	LL	19.5	22.7	27.2	11.5	17.0	.45	22.8
83	Oberlin*	LL	19.5	23.0	27.0	11.8	16.9	.46	23.3
84	Soko-Banja	LL	19.6	23.2	26.9	11.6	17.2	.36	22.7
85	Vårvik	LL	20.6	22.0	29.0	12.3	16.4	.62	24.6
86	Kernouve	H	No olivine found			8.5	18.8	.48	16.5

* Meteorites are finds.

† On the basis of the 'superior' analysis by *Prior* [1918], *Urey and Craig* [1953] classified the chondrite Homestead as belonging to the L group. This is in agreement with the results of the X-ray diffraction analyses of the silicates (Mason, personal communication) and the electron microprobe analyses of coexisting olivines and rhombic pyroxenes (this paper). According to the planimetric integration analyses of three large polished sections (total measured area 46.3 cm²) from two collections (Mineralogical Institute, Humboldt University, Berlin, Germany, and Mineralogical Institute, University of Greifswald, Germany) this meteorite has recently been classified as a H-group chondrite [*Keil*, 1962a, b]. Since Homestead is classified as a polymict breccia [*Prior and Hey*, 1953], it is an intriguing thought that this meteorite might be a mixture of L- and H-group fragments. However, Mason's suggestion that the Berlin and Greifswald sections might be mislabeled pieces of some other chondrites should be considered as a likely explanation (Mason, personal communication).

‡ The stone meteorite Temple has formerly been classified as being an achondrite (American Meteorite Laboratory, Denver, Colorado); however, it was found to be a typical L-group chondrite.

§ The Ramsdorf pyroxene is clinopyroxene (Mason, personal communication).

tent is considerably lower. For this reason the group constituted of Soko-Banja chondrites should properly be designated the low iron–low metal (or LL group) of chondrites.

Five among the 86 chondrites listed in Table 3 were found to belong to the LL group. These are Cherokee Springs, Dhurmsala, Oberlin, Soko-Banja, and Vårvik. The Fe/(Fe + Mg)

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TABLE 4. Average Composition of Olivine and Rhombic Pyroxene in LL-, L-, and H-Group Chondrites

| | Number of Chondrites | Olivine | | | Rhombic Pyroxene | | | |
| | | Weight % | | Mole %, Fe | Weight % | | | Mole %, Fe |
Group		Fe	Mg	Fe + Mg	Fe	Mg	Ca	Fe + Mg
LL	5	19.6	22.8	27.3	11.7	16.9	0.50	23.1
L	44	17.2	24.3	23.6	10.4	17.6	.50	20.5
H	36	13.3	26.6	17.9	8.4	18.9	.42	16.2
Total chondrites	85	15.7	25.1	21.4	9.6	18.1	.47	18.9

TABLE 5. Classification of Chondrites into LL, L, and H Groups on the Basis of Chemical-Mineralogical Parameters

Classification	LL Group A, Average B, Range in Composition	L Group A, Average B, Range in Composition	H Group A, Average B, Range in Composition	References
Bulk iron, on the basis of 'superior' bulk chemical analyses (weight %)	A. 20.87 (7)* B. 19.85–22.55	A. 21.82 (30) B. 20.55–23.33	A. 27.52 (27) B. 25.34–30.88	*Craig* [1964]
Ratio Fe/Ni in metallic nickel-iron, on the basis of 'superior' chemical analyses	A. 3.57 (7)	A. 6.87 (30)	A. 10.90 (27)	*Craig* [1964]
Metallic nickel-iron, on the basis of planimetric integration analyses of polished sections (weight %)	A. 2.64 (3)† B. 1.72–3.23	A. 6.85 (38)‡ B. 4.40–11.65	A. 16.72 (28)§ B. 14.17–19.81	*Keil* [1962a, b]
Ratio Fe/(Fe + Mg) in olivine (mole %)	A. 27.3 (5) B. 29.0–26.3	A. 23.6 (44) B. 24.6–21.6	A. 17.9 (36) B. 19.4–16.1	This paper
Ratio Fe/(Fe + Mg) in rhombic pyroxene (mole %)	A. 23.1 (5) B. 24.6–22.2	A. 20.5 (44) B. 21.7–17.9	A. 16.2 (36) B. 17.2–14.7	This paper
Specific gravity	A. 3.48‖ (10) B. 3.44–3.54	A. 3.52 (87) B. 3.26–3.75	A. 3.69¶ (62) B. 3.50–3.90	Based on *Pokrzywnicki* [1959] and *Keil* [1962b]

* The number of chondrites measured and included in the averages is given in parentheses.

† The chondrites Dhurmsala, Ensisheim, and Mainz, formerly classified into the L group [*Keil*, 1962a, b] have been included in the average for the LL group. According to the metallic nickel-iron content and to the Fe/(Fe + Mg) ratios in olivine and rhombic pyroxene, the Dhurmsala meteorite is a typical LL-group chondrite. However, the classification of the Ensisheim and Mainz chondrites into the LL group is somewhat uncertain, since it is based on only one parameter, namely, the metallic nickel-iron content.

‡ The average includes the low value (1.56%) of the Ergheo chondrite. This meteorite was picked up five years after the fall and, therefore, is considerably weathered. The low metallic nickel-iron value may well be due to this weathering; however, the microprobe analyses of olivine and rhombic pyroxene in this meteorite confirm its classification into the L group.

§ Excluded from this average are the chondrites Hvittis, Pillistfer, and Lance, since they belong to separate groups (enstatite chondrites and ornansites, respectively). In addition, the chondrite Homestead has been excluded from the average, since the slabs investigated were probably mislabeled (cf. footnote to Table 3).

‖ From this average, the doubtful value of the chondrite Guidder (3.92) has been excluded.

¶ From this average, the doubtful values of the chondrites Bowden (3.39), Cosina (3.10), and Hedeskoga (3.17) have been excluded.

TABLE 6. Comparison of the Mole Per Cent Ratios Fe/(Fe + Mg) As Calculated from FeO and MgO of 'Superior' Bulk Chemical Analyses with the Fe/(Fe + Mg) Ratios in Olivine and Rhombic Pyroxene As Obtained by Microprobe Analyses

| No.* | Name | Group | This Paper; Mole % Ratios Fe/(Fe + Mg) | | Chemical Analyses Mole % Ratios Fe/(Fe + Mg) As Calculated from FeO and MgO of Bulk Chemical Analyses | Reference |
			Olivine	Rhombic Pyroxene		
3	Mcrua	H	16.5	15.7	15.3	*Tipper* [1925]‡
9	Breitscheid	H	17.4	16.1	14.8	*Vilcsek* [1959]
8	Ochansk	H	17.5	15.6	14.4	*Wiik* [1956]
7	Allegan	H	17.5	16.0	17.8	*Merrill and Stokes* [1900]‡
6	Ställdalen	H	17.7	16.0	16.5	*Lindström* [1877]‡
16	Hessle	H	17.8	16.1	20.8	*Nordenskiold* [1870] (Lindstrom)‡
22	Collescipoli	H	17.8	16.3	12.4	*Wahl* [1950a] (Wiik)‡
18	Tomhannock Creek†	H	17.9	16.3	26.0	*Mason and Wiik* [1960]
27	Beaver Creek	H	18.3	16.0	19.4	*Howell et al.* [1894]‡
29	Forest City	H	18.3	16.0	16.0	*Kunz* [1890] (Eakins)‡
30	Oakley†	H	18.3	16.8	19.6	*Wahl* [1950b] (Wiik)‡
28	Estacado†	H	18.4	16.6	23.5	*Howard and Davison* [1906]‡
31	Djati-Pengilon	H	18.7	16.8	26.8	*Daubree* [1887] (Retgers)‡
32	Ekeby	H	18.9	16.8	21.0	*Hadding* [1940]‡
42	Homestead	L	22.0	19.9	21.9	*Prior* [1918]‡
57	Chantonnay	L	23.3	20.5	24.9	*Rammelsberg* [1870]‡
48	Kyushu	L	23.3	20.6	26.0	*Mason and Wiik* [1961a]
60	New Concord	L	23.6	20.4	20.9	*Mason and Wiik* [1961b]
58	Chateau Renard	L	23.7	20.5	21.9	*Mason and Wiik* [1961b]
70	Bruderheim	L	23.8	20.7	24.0	*Duke et al.* [1961]
50	Forksville	L	23.9	20.8	28.4	*Merrill* [1927] (Shannon)‡
69	Saint Michel	L	23.9	21.2	23.5	*Borgström* [1912]‡
79	Harleton	L	24.1	20.7	29.8	*Clarke* [1962]
72	Coon Butte†	L	24.3	20.8	24.7	*Mallet* [1906]‡
78	Girgenti	L	24.3	21.1	27.7	*Rath* [1869]‡
80	Mocs	L	24.4	20.8	20.9	*Mason and Wiik* [1961b]
61	Albareto	L	24.4	21.7	25.8	*Gallitelli* [1939]‡
77	Bjurböle	L	24.5	21.2	22.3	*Ramsay and Borgström* [1902]‡
74	Holbrook	L	24.6	20.8	20.8	*Mason and Wiik* [1961c]
84	Soko-Banja	LL	26.9	22.7	28.0	*Prior* [1916b]‡
86	Kernouve	H	...	16.5	21.7	*Pisani* [1869]‡

* Number in column one refers to Table 3.
† Meteorites are finds.
‡ 'Superior' chemical analyses according to *Urey and Craig* [1953].

ratios for olivine and rhombic pyroxene are distinctly higher in Vårvik than in the four other chondrites of this group. This may possibly suggest the existence of a fourth group, or of a subgroup; since adequate statistics are lacking, this chondrite has simply been included in the LL group.

The data presented indicate that the iron content in olivine and rhombic pyroxene can be an excellent criterion for classifying a specific chondrite in one of the three groups. Table 3 shows that the spread in the iron content of olivine and rhombic pyroxene within each group is rather small. In the LL group it varies from 19.0 to 20.6 (olivine) and 11.2 to 12.3 (rhombic pyroxene); in the L group it varies from 15.8 to 17.9 (olivine) and from 9.0 to 10.9 (rhombic pyroxene); and in the H group it varies from

RATIO $\frac{Fe}{Fe + Mg}$ IN MOL PERCENT
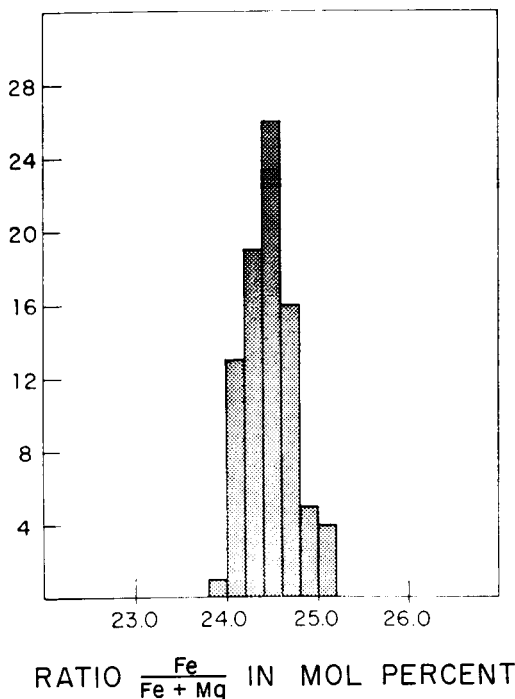
Fig. 3. Chondrite Bjurböle. Frequency distribution of the mole per cent ratios Fe/(Fe + Mg) in olivine. Eighty-four analyzed individual olivine crystals from seventeen different chondrules average 24.5 ± 0.2₆.

11.9 to 14.3 (olivine) and from 7.7 to 8.8 (rhombic pyroxene). As illustrated in Figure 4, all three groups are clearly defined. In Figures 7 and 8, the Fe/(Fe + Mg) ratios are plotted in frequency distribution diagrams for olivine and rhombic pyroxene. Again, the three groups, and likewise the sharp boundaries between them, are clearly recognizable.

The calcium content in the rhombic pyroxene, which varies within rather narrow limits, is not significantly different in chondrites of the LL, L, and H groups, although there may be a slight

tendency toward higher calcium content in those of the L group than in those of the H group (Figures 9 and 10).

The average values for Fe, Mg, and Fe/(Fe + Mg) in olivine, and for Fe, Mg, Ca, and Fe/(Fe + Mg) in rhombic pyroxene, of the chondrites listed in Table 3, are given in Table 4, separated into LL, L, and H groups, and a column for the total chondrites investigated. In Table 5 the various characteristic chemical-mineralogical parameters for LL, L, and H groups are compiled. On the basis of these parameters, the definite classification of a given chondrite into its proper group is possible.

DISCUSSION

The importance of the composition of coexisting olivines and pyroxenes for considerations related to the history of rocks has early been realized, and many important papers have been published dealing with chemical analyses and with theoretical calculations of these assemblages in plutonic, volcanic, and metamorphic rocks [e.g., *Atlas*, 1952; *Bartholome*, 1962; *Bowen and Schairer*, 1935; *Brown*, 1957; *Brown et al.*, 1961; *Hess*, 1941, 1949; *Hess and Phillips*, 1938, 1940; *Hori*, 1956; *Howie*, 1955; *Kuno*, 1954; *Kuno and Nagashima*, 1952; *Mueller*, 1960, 1961; *Muir*, 1951; *Muir and Tilley*, 1957, 1958; *O'Hara*, 1960; *Poldervaart*, 1947; *Poldervaart and Hess*, 1951; *Ramberg*, 1952; *Ramberg and De Vore*, 1951; *Ross et al.*, 1954; *Sahama and Torgeson*, 1949a, b; *Schairer and Boyd*, 1957; *Wager and Deer*, 1939; *Wilson*, 1960; *Yoder and Sahama*, 1957].

Systematic study of coexisting olivines and rhombic pyroxenes in meteorites has been much less wide spread. Most important are the studies of *Hess and Henderson* [1949], *Mason* [1962a], *Mueller* [1963], *Prior* [1916a], *Ringwood* [1961], and *Wahl* [1907].

TABLE 7.   Chondrite Bjurböle: Average Composition of 84 Olivine Crystals from 17 Individual Chondrules and 15 Rhombic Pyroxene Crystals from 6 Individual Chondrules

| | Weight % | | | Mole % |
Mineral	Fe	Mg	Ca	Fe/(Fe + Mg)
Olivine	17.8 ± 0.2	23.9 ± 0.2		24.5 ± 0.3
Rhombic pyroxene	10.8 ± 0.4	17.5 ± 0.3	0.34 ± 0.1	21.2 ± 0.3
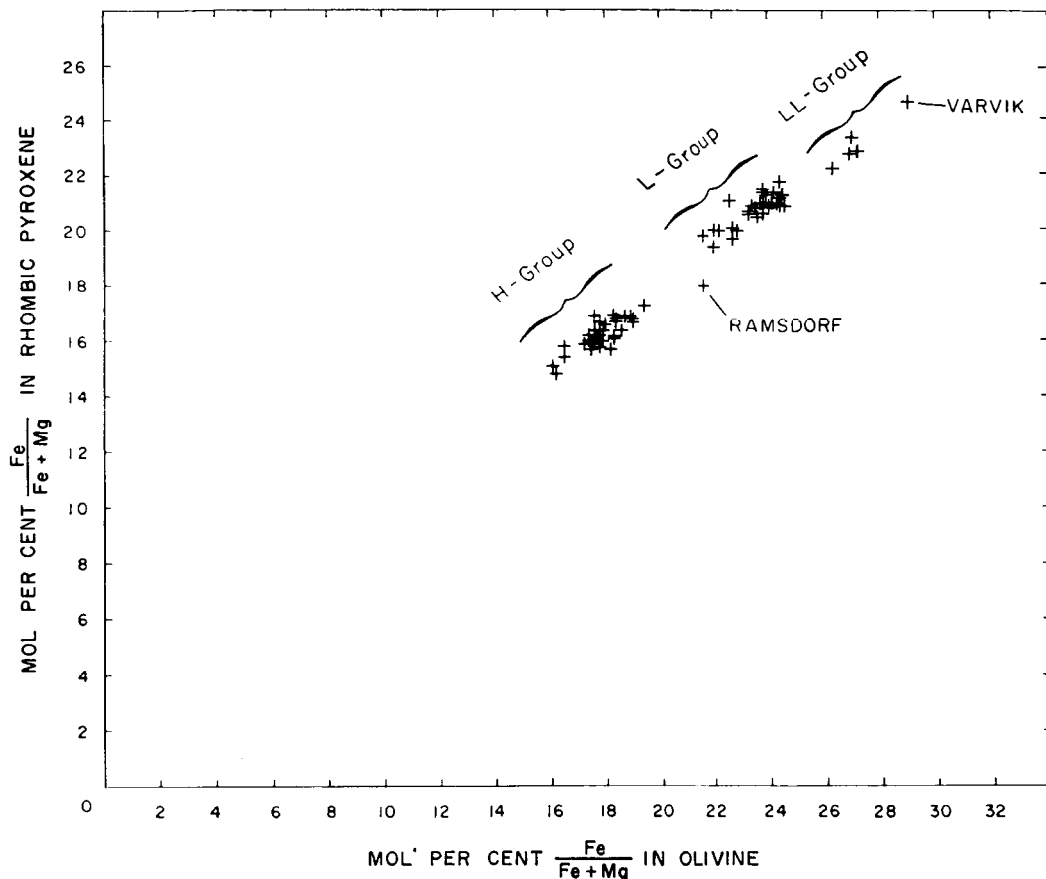
Fig. 4. Ratios Fe/(Fe + Mg) in olivine plotted against ratios Fe/(Fe + Mg) in rhombic pyroxene for the chondrites listed in Table 3 (in mole per cent).

Mason [1962a], who studied the composition of olivines by means of refractive index measurements in a large number of chondrites, published a frequency distribution diagram of the Fe/(Fe + Mg) ratios in olivines, which agrees for the most part with Figure 7 of the present study. His Fe/(Fe + Mg) values seem to be systematically higher than those determined in the present study although the deviation is slight, amounting to only one mole per cent Fe/(Fe + Mg). The LL-, L-, and H-group peaks are recognizable in his figures, but the boundaries between the groups are not so distinct as they are in Figure 7 of the present study, because the error involved in the technique Mason used is considerably higher, being of the order of 10 per cent, which amounts to ±1.0 to ±1.5 per cent Fe.

Note added in manuscript: Mason [1963], in a recent paper, published the fayalite contents of olivines of some 800 chondrites obtained by X-ray diffraction techniques. His values agree well with the present ones, although there is a slight systematic difference of about 1 mole per cent fayalite between them. The apparent large differences in case of Barbotan (Mason, Fa_{24}; present paper, $Fa_{17.9}$) and Mooresfort (Mason, Fa_{19}; present paper, $Fa_{22.2}$) is due to mislabeled specimens that Mason (private communication) investigated. His new values (Barbotan, Fa_{19}; Mooresfort, Fa_{22}) are in good agreement with the ones obtained in the present study.

Classification of chondrites. Several classifications of meteorites and particularly of chondrites have been proposed in the past years [*Brezina,* 1904; *Prior,* 1916a, 1920; *Urey and*

Craig, 1953; Boato, 1954; Wiik, 1956; Mason, 1962a; Yavnel, 1962, 1963], but a number of the supposedly 'newly discovered' groups were found to be identical with groups that earlier authors had already recognized and named. This led to the existence of a number of different terms for the same thing and has made the proper classification of chondrites complicated and often confusing, particularly for nonspecialists in this field. Some further confusion is caused by improper use of some mineral names, particularly in the cases of the bronzite-olivine and hypersthene-olivine chondrites. It has been shown in the present paper that the ordinary chondrites do not contain rhombic pyroxene with hypersthene composition, but instead contain exclusively rhombic pyroxene with bronzite composition. The nomenclature of rhombic pyroxenes as suggested by Poldervaart [1947] and by Poldervaart and Hess [1951] is widely accepted in modern literature and handbooks on terrestrial rocks, and it should be adopted for meteorite minerals as well. The classification suggested by Poldervaart [1947] is primarily chemical, and for the rhombic pyroxenes it is as follows: enstatite 0 to 10, bronzite 10 to 30, hypersthene 30 to 50, ferrohypersthene 50 to 70, eulite 70 to 90, and orthoferrosilite 90 to 100 mole per cent $FeSiO_3$. In fact, the composition
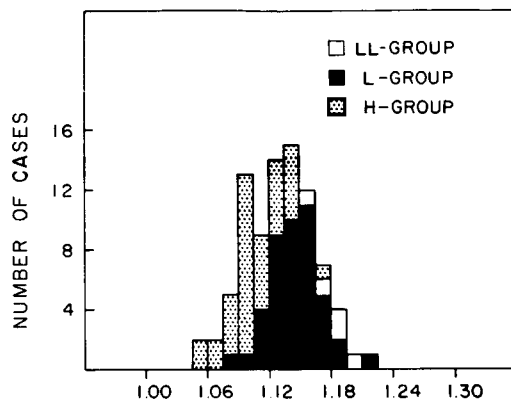
Fig. 5. Frequency distribution of the ratios $[Fe/(Fe + Mg)]_{olivine}/[Fe/(Fe + Mg)]_{rh.\ pyroxene}$ for the chondrites listed in Table 3.

of the rhombic pyroxenes in bronzite-olivine and hypersthene-olivine chondrites varies within the ranges of 17.2 to 14.7 and 21.7 to 17.9 mole per cent, respectively; that is to say, per definition the rhombic pyroxene in both bronzite-olivine and hypersthene-olivine chondrites is bronzite. To avoid misunderstanding, it is therefore recommended that the names 'high (H) and low (L) iron groups' of Urey and Craig [1953] be used instead. In the following paragraph a chondrite classification is proposed
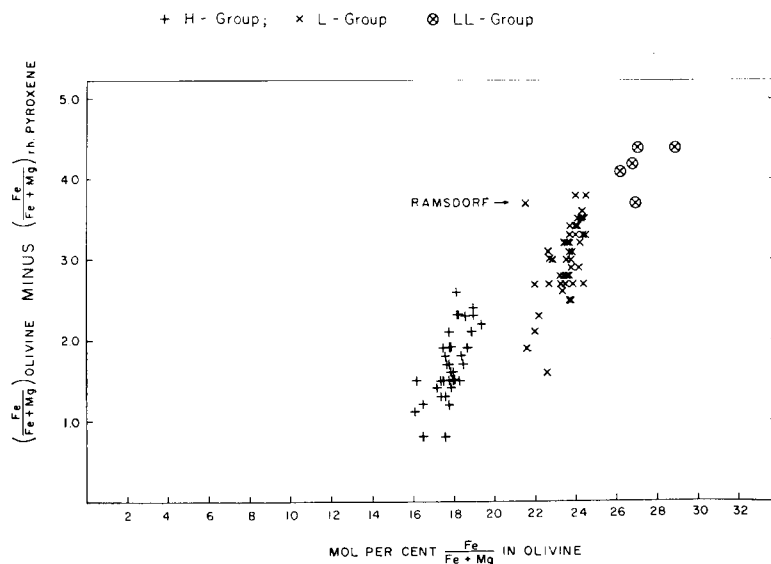
Fig. 6. The difference $[Fe/(Fe + Mg)]_{olivine} - [Fe/(Fe + Mg)]_{rh.\ pyroxene}$ in chondrites increases with increasing oxidized iron.
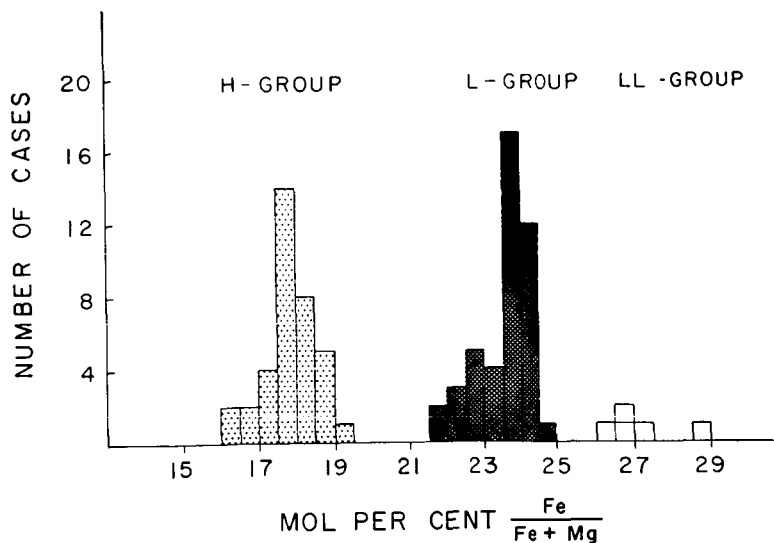
Fig. 7. Frequency distribution of the mole per cent ratios Fe/(Fe + Mg) in olivine for the chondrites listed in Table 3.

which is based on the best analytical data available. So as not to complicate the matter, we have attempted to use names that have some chemical-mineralogical significance and that are most commonly used by the majority of investigators in this field. For the LL, L, H, and HL groups of chondrites, the classification is based on two parameters, the total iron and the metallic nickel-iron. The LL, L, and H groups have been described in detail in the preceding section, and their characteristic chemical-mineralogical parameters have been summarized in Table 5. The group of chondrites consisting of meteorites of the Ornans type (the pigeonite chondrites of *Mason* [1962a]) have a total iron content similar to that in H-group chondrites, while their metallic nickel-iron content is considerably lower and varies about 1 to 4 weight per cent [*Wiik*, 1956]. Therefore this group should properly be named the high iron–low metal (HL) group. At the present time the enstatite chondrites cannot be classified in accordance with the principle outlined above, since the available analyses show a highly varying amount of total iron. The total iron values range all the way from L-group to H-group chondrites, and even considerably above H-group chondrites. For this reason the customary name enstatite chondrite has been retained. The total iron content of the carbonaceous chondrites is similar to that of H-group

chondrites, while their content of metallic nickel-iron is essentially zero. The classification principles mentioned have not been applied to this group because then the two subgroups of the carbonaceous chondrites (type 1 and type 2 of *Wiik* [1956]) would be merged into one single group. Yet, basic mineralogical and chemical differences other than total iron content between the two subgroups are so striking that it seemed advisable to adopt the classification into type 1 and type 2. The type 3 carbonaceous chondrites of *Wiik* [1956] are so characteristically different from the type 1 and type 2 that they seem to belong in still a separate group, the HL group, or pigeonite chondrites of *Mason* [1962a]. Type 1 carbonaceous chondrites do not contain chondrules and therefore (per definition) should not be designated chondrites at all. However, they have customarily been retained in that classification because they seem to be closely related to type 2 carbonaceous chondrites. It is hoped that further studies may allow a more precise mineralogical classification in the future.

To make the following compilation as complete as possible, other names presently in use have also been listed.

A. *Enstatite chondrites* [*Prior*, 1920]. Daniels Kuil type chondrites [*Prior*, 1916a]; group 1 chondrites [*Yavnel*, 1962, 1963].
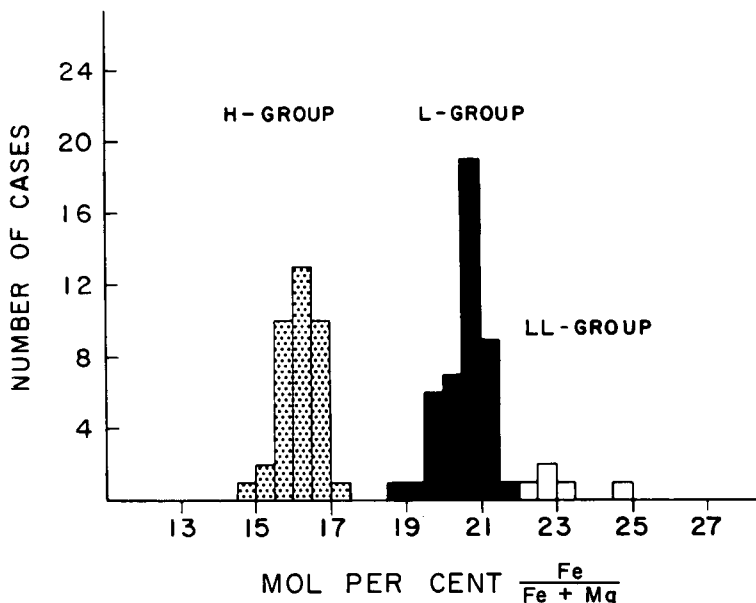
Fig. 8. Frequency distribution of the mole per cent ratios $Fe/(Fe + Mg)$ in rhombic pyroxene for the chondrites listed in Table 3.

B. *High iron (H)-group chondrites* [*Urey and Craig*, 1953]. Cronstad type chondrites [*Prior*, 1916a]; bronzite-olivine chondrites [*Prior*, 1920]; group 2 chondrites [*Yavnel*, 1962, 1963].

C. *Low iron (L)-group chondrites* [*Urey and Craig*, 1953]. Baroti type chondrites [*Prior*, 1916a]; hypersthene-olivine chondrites [*Prior*, 1920]; group 3 chondrites [*Yavnel*, 1962, 1963].

D. *Low iron–low metal (LL)-group chondrites.* Soko-Banja type chondrites [*Prior*, 1916a];[4] these were included in the hypersthene-olivine chondrites by *Prior* [1920] and *Mason* [1962a]; group 4 chondrites [*Yavnel*, 1962, 1963].

E. *High iron–low metal (HL)-group chondrites.* Ornansites [*Brezina*, 1904]; included in the Soko-Banja group chondrites [*Prior*, 1916a] and in the hyper-

sthene-olivine chondrites [*Prior*, 1920]; type 2 carbonaceous chondrites [*Boato*, 1954]; type 3 carbonaceous chondrites [*Wiik*, 1956]; pigeonite-olivine chondrites [*Mason*, 1962a]; group Va chondrites [*Yavnel*, 1963].

F. *Carbonaceous chondrites of type 1 and type 2* [*Wiik*, 1956].

1. Included in the Soko-Banja group chondrites [*Prior*, 1916a], and in the hypersthene-olivine chondrites [*Prior*, 1920]; group Vc chondrites [*Yavnel*, 1963].

2. Included in the Soko-Banja group chondrites [*Prior*, 1916a], in the hypersthene-olivine chondrites [*Prior*, 1920], and in the type 1 carbonaceous chondrites of *Boato* [1954]; group Vb chondrites [*Yavnel*, 1963].

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[4] *Prior* [1916a] had in his Soko-Banja group nine chondrites which (on the basis of the new analytical data) actually belong to the L group of chondrites. These nine are: Albareto, Alfianello, Bachmut, Bluff, Eli Elwah, Erghco, Knyahinya, Mocs, and Nerft. He also originally included the carbonaceous chondrites and ornansites in this group, although they constitute separate groups.

It has been shown in preceding sections that the LL, L, and H groups are defined by several mineralogical and chemical parameters (Table 5). It has been pointed out that on the basis of these parameters the classification of a given chondrite into one of these groups is possible. However, *Urey* [1964] has recently pointed out that
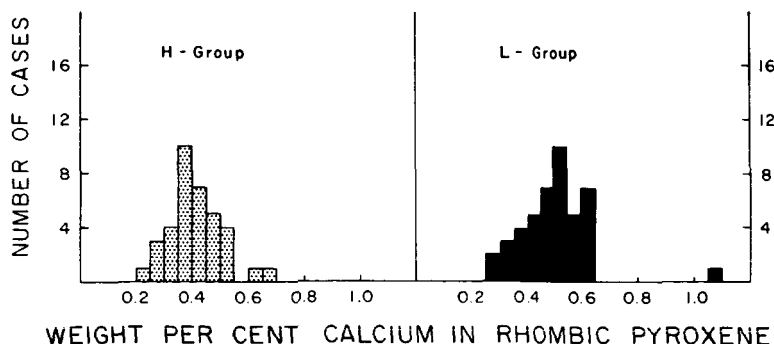
Fig. 9. Frequency distribution of the calcium content of rhombic pyroxenes in the chondrites listed in Table 3.

that in some unusual cases different classifications were possible for a given chondrite on the basis of these parameters. At the moment it is not clear whether this is due to (a) the existence of chondrites composed of fragments from different groups, (b) the existence of chondrites composed of a mixture of, for instance, a silicate matrix of one group with metallic nickel-iron of another group, or (c) errors in the analytical results which might be caused by actual analytical errors and/or sampling errors due to use of terrestrially weathered chondrites or similar causes. At the present time, explanation (c) appears most reasonable. However, more detailed studies are necessary to decide this question.

Chemical analyses of chondrites and Prior's rule. One result of the microprobe analyses of olivines and rhombic pyroxenes in chondrites during the present study is that the range in composition of these minerals in the different chondrites has been discovered to be surprisingly small, particularly if it is compared with the highly varying amounts of metallic nickel-iron in chondrites [*Keil,* 1962a, b]. Table 5 gives an indication of this striking situation. Figure 11 shows that the metallic nickel-iron content in the L-group chondrites, for instance, varies from 4.40 to 11.65 weight per cent, whereas the Fe content in olivines of the same group varies only from 17.9 to 16.3 and for rhombic pyroxene from 10.9 to 9.0 weight per cent. The amount of metallic nickel-iron has been plotted against the iron content in olivine and rhombic pyroxene of chondrites. Most of the metallic nickel-iron values were obtained by planimetric integration of large polished sec-

tions [*Keil,* 1962a, b]; the others are from 'superior' chemical analyses as given by *Urey and Craig* [1953], and from others published more recently by several other investigators (see Table 2). As has already been pointed out [*Keil,* 1962a, b], there is a systematic difference between the metallic nickel-iron contents obtained by chemical analyses and by planimetric integration. *Wiik* [1956] showed, on the basis of recent analyses, that the iron content of chondrites as given by *Urey and Craig* [1953] is probably somewhat too high. The results of the planimetric integration, on the other hand, could be somewhat too low, since extremely small grains might have been overlooked under the microscope or might have been lost during the
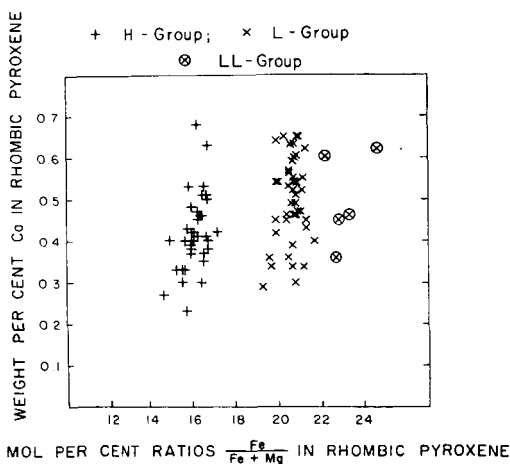

Fig. 10. Calcium content in the rhombic pyroxenes of the chondrites listed in Table 3.

process of polishing the samples. However, this deviation is likely to be less than 1 per cent nickel-iron. Yet the spread in the contents of metallic nickel-iron, as obtained by planimetric integration, seems to be real. Figure 11 shows that in spite of differing amounts of metallic nickel-iron the Fe content in olivine and rhombic pyroxene varies within narrow limits. The most important fact, however, is that within a given group there is no clear relationship between the amount of metallic nickel-iron and the Fe content in olivine and rhombic pyroxene of chondrites. The broken lines in Figure 11 were calculated from the average composition of each group, assuming straight reduction-oxidation of iron and taking into account the resulting changes in mineralogical composition; that is, an increase of divalent iron increases the amount of olivine but decreases the amount of rhombic pyroxene, etc. The calculations are based on the averages given by *Urey and Craig* [1953] (Ni content); by *Keil* [1962a, b] (metallic nickel-iron and troilite contents); and by *Mason* [1962b] (feldspar and olivine-rhombic

pyroxene ratios). The average composition of olivine and rhombic pyroxene was taken from the numbers given in the present study. The disagreement of the slope of these lines with the actually measured values indicates that the second part of Prior's rule in its original sense ('the less the amount of nickel-iron in chondritic stones . . . the richer in iron are the magnesium silicates') is not valid.

However, if the chemically obtained metallic nickel-iron values (circles in Figure 11) were disregarded, then some relation between metallic nickel-iron and divalent iron within single groups (particularly H group) could possibly be inferred, but any such relation is by no means general and does not follow the theoretical red-ox lines in Figure 11. Since the metallic nickel-iron values might still be affected by an error of some 5 per cent, an attempt was made to correlate the chemically obtained nickel values with the amount of divalent iron in olivine and rhombic pyroxene, but no characteristic relation with the few 'superior' nickel analyses available in the literature has been observed.
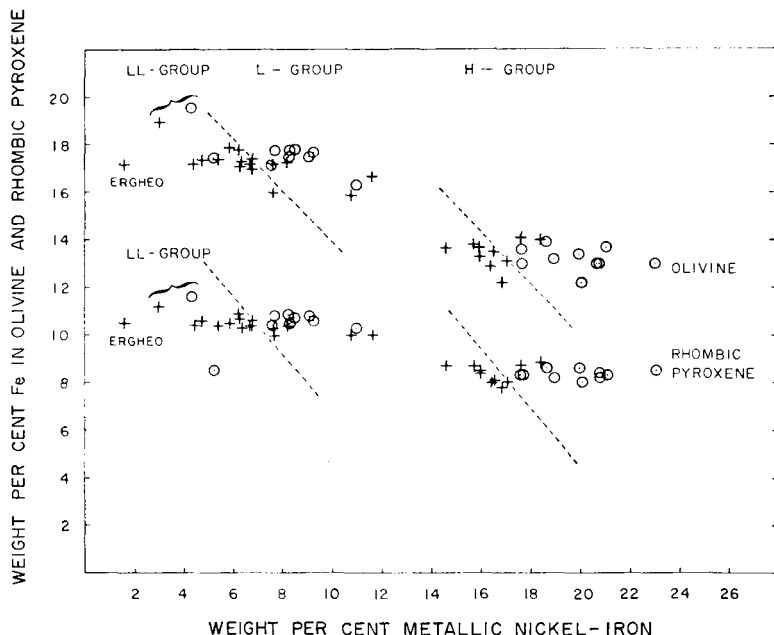

Fig. 11. Relation between the amount of metallic nickel-iron and oxidized iron in olivine and rhombic pyroxene. The metallic nickel-iron values of chondrites (plus signs) were obtained from papers by *Keil* [1962a, b]; the values symbolized by circles were obtained from 'superior' chemical analyses of several sources (cf. Table 2). The dashed lines were calculated from the group averages assuming straight reduction-oxidation of iron.

Accurate nickel determinations (~1 per cent of the values) on sufficiently large samples seem to be needed to settle this question.

On the basis of the average composition of L- and H-group chondrites as given above, a simple calculation has been made to evaluate a reduction-oxidation process accompanied by removal of metallic nickel-iron.

Starting with the average H-group composition, it was found that about 4.5 per cent metallic iron has to be oxidized to change the composition of the proper amounts of olivine and rhombic pyroxene to the values of the L-group chondrites. While some iron is being oxidized into the divalent state, the nickel remains reduced in the metallic nickel-iron, thus increasing its nickel content in an amount corresponding to the 4.5 per cent metallic iron being oxidized. A certain amount of the metallic nickel-iron has to be removed to give the amount now observed in the average of the L group. After the removal of the proper amount, the amount of nickel left in the chondrite can be calculated. The calculated value (~1.18 per cent Ni) agrees well (within 8 per cent) with the average nickel content (1.06 per cent) in the L group [*Urey and Craig*, 1953]. This calculation does not necessarily imply that the L-group chondrites were formed by oxidation of pre-existing H-group chondrites, but it indeed seems to support *Ringwood*'s [1961] suggestion that 'the low-iron group is essentially a member of the parental high-iron group from which a small proportion of iron has been removed.' A further discussion of such a model and some of its difficulties will be given in the next section.

On this basis, it seems that, although some reduction-oxidation of iron might have occurred, Prior's rule cannot be applied quantitatively because removal of metallic nickel-iron is necessary to account for a relation of oxidized versus metallic iron as observed in Figure 11.

It has already been mentioned that after *Prior*'s [1916a, 1920] pioneering work most subsequent workers have supported the second part of his rule. Their studies were mainly based on a comparison of metallic nickel-iron with FeO values obtained by bulk chemical analyses. Those data seem to support strongly the second part of that rule. However, the data of the present study make the use of chemically obtained FeO

values doubtful. In fact, it seems as if the relation expressed in the second part of Prior's rule in its original sense is a direct result of erroneous FeO determinations by means of chemical analyses. The wet chemical determination of FeO in chondrites, which contain iron in metal, sulfides, and silicates, is known to be extremely difficult. It may be designated the most uncertain value in a chondrite analysis [*Wiik*, 1956], since it is derived by subtraction after three separate analyses. Usually in such an analysis the metallic nickel-iron is determined independently by magnetic separation or by using various solvents. Iron in the sulfide is calculated from the amount of sulfur present. A third determination gives the total iron. The FeO is then computed as follows:

$$Fe_{oxidized} = Fe_{total} - (Fe_{FeS} + Fe_{metal})$$

Generally, the value for FeS tends to be too high, since all the sulfur is calculated as FeS without taking into account the presence of some minor minerals such as CaS, $FeCr_2S_4$, and others. Much more serious are some other uncertainties which might, in particular, affect the value of the iron in the metal. Most important in this connection is the problem of sampling errors. The metallic nickel-iron is inhomogeneously distributed throughout a given meteorite [*Keil*, 1962a, b]. The use of too small samples for the analysis could influence the results considerably. In addition, some of the metallic nickel-iron is included in silicates and will only partly be dissolved in the analytical procedure. Although correction can be made by measuring the Ni content of the silicate part, a considerable error may be introduced owing to inhomogeneous Ni distribution. Furthermore, broken surfaces of chondrites show that even in case of fresh falls the nickel-iron oxidizes and becomes surrounded by a brownish oxide rim. As a result, the values for the metal will be too low, and this, in turn, brings up the values for the oxidized iron according to the formula. In fact, any error in the value of the metallic iron will affect the oxidized iron values in the opposite direction, thus creating artificially a relation such as is expressed in the second part of Prior's rule. Chemical error as the cause for this accidentally created rule, which was based on bulk chemical analyses, was already proposed by *Urey and Craig* [1953], a point of view which
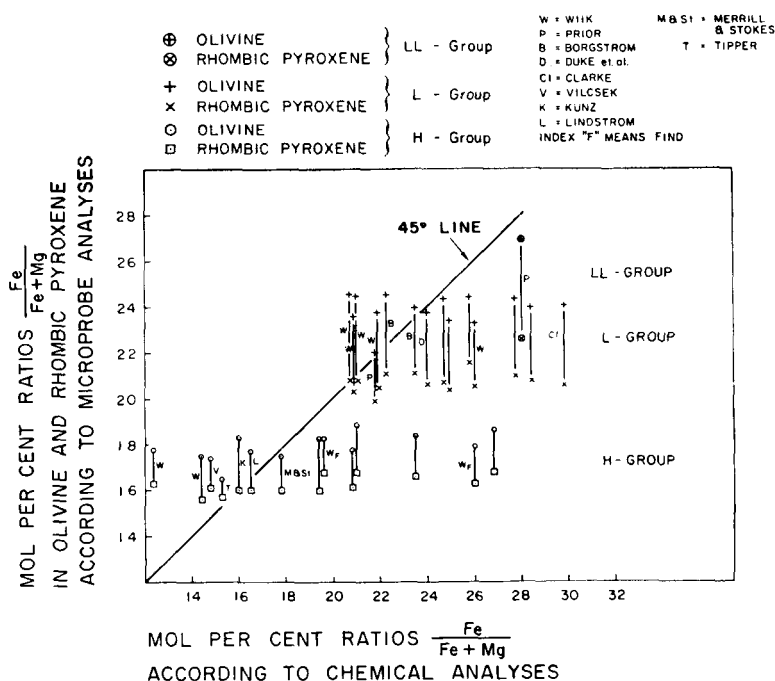
Fig. 12. Mole per cent ratios Fe/(Fe + Mg) as calculated from FeO and MgO of 'superior' bulk chemical analyses versus ratios Fe/(Fe + Mg) in olivine and rhombic pyroxene of chondrites obtained by microprobe analyses.

appears to be favored by the data of the present study. This is illustrated in Figure 12 on the basis of the numbers compiled in Table 6. In Figure 12 the Fe/(Fe + Mg) values according to chemical analysis are plotted against the Fe/(Fe + Mg) ratios of olivine–rhombic pyroxene pairs of different chondrites according to the microprobe analyses. On the assumption that olivine and rhombic pyroxene are the only major minerals containing FeO, and that both microprobe and chemical analyses are correct, the lines connecting coexisting olivines with rhombic pyroxenes for a given chondrite should intersect a 45° line. This happens for only some of the chemical analyses, whereas usually the Fe/(Fe + Mg) values given by the chemical analyses are considerably higher than the microprobe results. Besides, the spread in the chemically obtained Fe/(Fe + Mg) values is much higher than for the microprobe data. Only a few analyses seem to be 'superior' with regard to the FeO, such as several by Wiik, Borgström, and Prior. Nevertheless, even a few of the more recent analyses, such as those by Wiik, Clark,

and others, deviate markedly, although for the two finds analyzed by Wiik this is very likely due to terrestrial oxidation of metal to oxide.

It is not likely that some minerals with high the FeO, such as several by Wiik, Borgström, cause these deviations, since the more reliable chemical analyses agree better with the data of the present study. Furthermore, a special search for minerals containing large amounts of divalent iron in the fine-grained matrix of the Kyushu chondrite, for which a marked discrepancy between chemical analysis and the present data is apparent (Table 6), was negative. No such minerals have been found by stepping with the probe across the fine-grained matrix; nor have any silicates with iron contents higher than that of olivine been observed in any of the other ordinary chondrites investigated.

On the origin of chondrules and chondritic meteorites. Many models have been proposed for the origin of chondrules and chondritic meteorites. Most investigators, however, seem to agree that chondrules must have formed through rapid crystallization of liquid droplets, as is in-

dicated by the presence of devitrified glass in chondrules, the frequent occurrence of skeleton crystals, the droplike shape of the chondrules, the presence of high-temperature plagioclase, and the occasional indentation of one chondrule by another. These droplets would later have accumulated to form chondrites. From the present results it seems clear that the composition of olivine and pyroxene with regard to iron content was essentially established when the crystals were formed. This is contrary to a hypothesis recently published by Wood [1962a, b; 1963a, b]. He suggested that molten silicate droplets could originate through condensation in a gas cloud of solar composition; in this case the silicates would have low iron content (<2 per cent Fe). Wood therefore suggested that the ferrous iron now present in olivine and pyroxene was introduced by diffusion in solid state from magnetite (Fe_3O_4), present in the matrix of the primitive chondrite, into the silicates of the chondrules during a subsequent metamorphic process. Although most chondrites have doubtless been recrystallized and metamorphosed, this apparently did not cause any major changes in the composition of the Mg-Fe silicates, but mainly resulted in changes of the structure, porosity, and compactness of the meteorites, as is discussed in detail below.

Chondrites of different groups (LL, L, and H groups) are characterized by typical Fe/(Fe + Mg) ratios of their olivines and rhombic pyroxene, as is illustrated in Figure 4. According to Wood's model, chondrites with higher Fe/(Fe + Mg) ratios within a given group should be highly recrystallized, while the ones with low ratios should be less recrystallized. To compare the degree of metamorphism[5] with the iron content of the silicates, thin sections of 35 analyzed chondrites were examined microscopically. In both L and H groups there are chondrites showing a wide range of metamorphism, from friable stones with pronounced chondritic structure to well-indurated ones with chondrules inseparable from, or even completely integrated with, the ground mass. However, no connection between degree of metamorphism, as determined in this

way, and composition of the olivines and rhombic pyroxenes was found. One example is the meteorite Tieschitz, a typical unmetamorphosed chondrite [Wood, 1962a, 1963b] which, however, contain olivines and pyroxenes with high, varying amounts of iron [Wood, 1962b]. (Microprobe analyses show up to 11.9 per cent Fe in olivine, and up to 8.9 per cent Fe in pyroxene.)

Another finding, which contradicts Wood's proposition that the iron content in the silicates of chondrites is secondary, concerns some rather unmetamorphosed chondrites like Murray [Fredriksson and Keil, 1964] and Chainpur (detailed microprobe results in Keil et al. [1964]). These very friable meteorites contain a high percentage of olivine and pyroxene, sometimes with extremely high content of ferrous iron (cf. Figures 13 and 14). Since these chondrites are in a rather unmetamorphosed stage they should, according to Wood's hypothesis, not contain any appreciable amounts of iron in the silicates. A characteristic feature of these chondrites is that they contain olivines and pyroxenes of highly varying composition (Murray: olivine 0.3 to 91.2, pyroxene 0.4 to 45.4, Figure 14; Chainpur: olivine 0.1 to 36.1, pyroxene 0.9 to 25.9, Fe/(Fe + Mg) mole per cent, Figure 13). As Fredriksson [1963] emphasized, it is unlikely that in an in situ recrystallization, as proposed by Wood, some olivine and pyroxene grains would remain as almost pure Mg silicates, while others, only a fraction of a millimeter away, would increase in iron to high concentrations, particularly in the presence of carbon. Of particular interest in this connection is the Chainpur chondrite. Several hundred olivine and pyroxene crystals were analyzed from 50 chondrules of different sizes. In Figure 13 some of the results are summarized. Since the crystals are zoned, the averages of the values measured in a given crystal have been plotted. The diagrams illustrate the variability in composition from crystal to crystal as discussed above. In addition, they indicate that smaller chondrules tend to contain less iron in olivines and pyroxenes than do the larger ones, a fact which again contradicts the possibility of a secondary origin of the iron content in these silicates. If the Fe/(Fe + Mg) ratios were due to diffusion in solid state of iron, the silicates in the small chondrules should be richer, or at least equally as rich, in iron as the silicates in the large ones.

[5] As defined by most earlier workers, including Wood, through the indistinctness of the chondrules from the matrix, the relative uniformity of grain size, appearance of the plagioclase, etc.
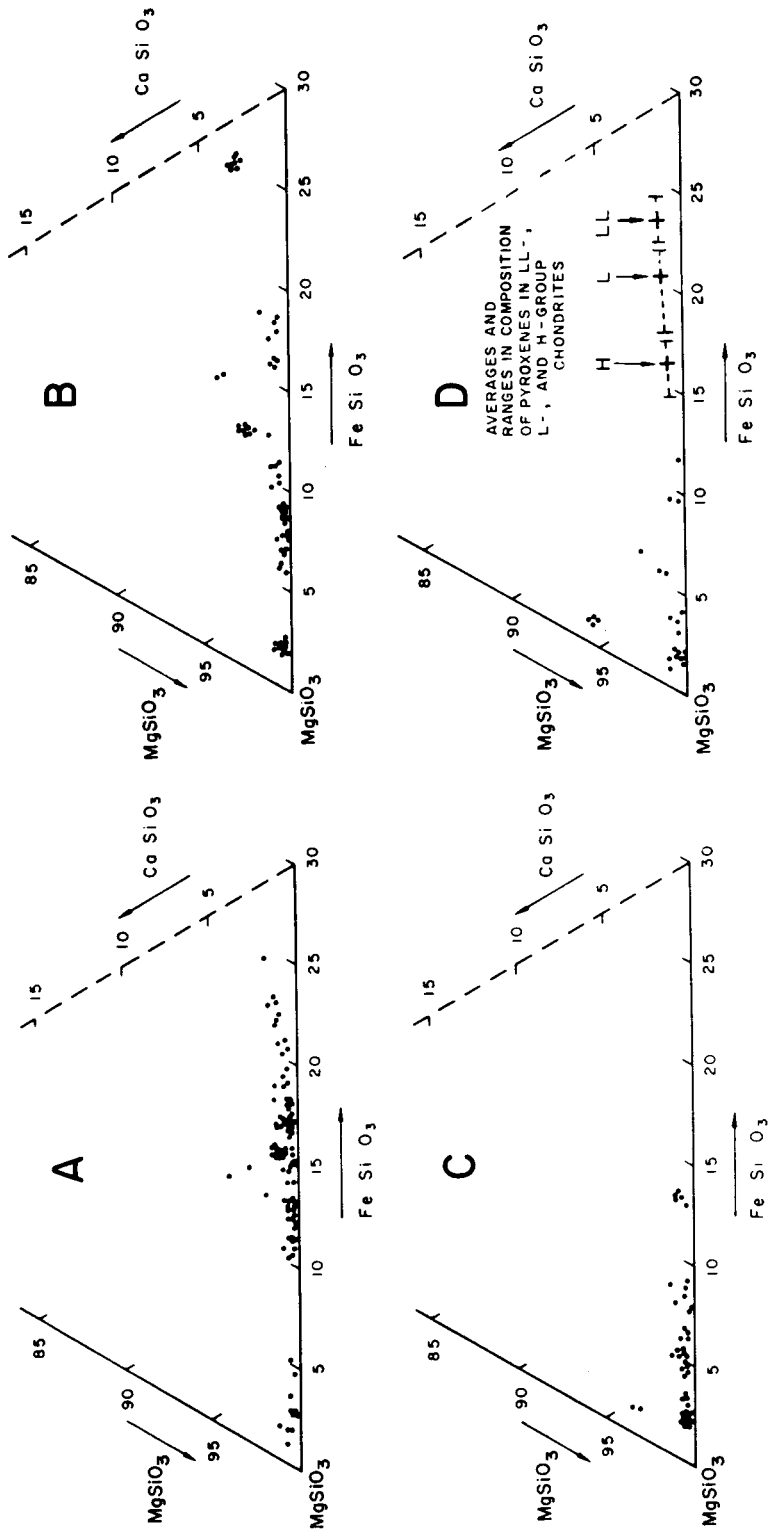
Fig. 13. Chondrite Chainpur. Composition of individual pyroxene crystals from individual chondrules, plotted in MgSiO₃-FeSiO₃-CaSiO₃ concentration triangles.

The olivines and pyroxenes in the Chainpur chondrite show marked zonal structure; that is, the core of the crystals is rich in Mg, while the iron content progressively increases toward the outer rims of the crystals. This is in accordance with what would be expected when olivine and pyroxene crystallize from a melt at a rapid rate, however, somewhat slower than in the quenched chondrules of ordinary chondrites.

These findings indicate that the composition of the chondrules was essentially established before they agglomerated.

As already explained above, chondrules appear to have originated by rapid cooling (quenching) of molten droplets, which then accumulated to form chondrites. In such a process it seems unlikely that olivine-rhombic pyroxene pairs would crystallize in equilibrium, although the almost constant ratios of $(Fe)_{olivine}/(Fe)_{rh. pyroxene}$ may seem to indicate this (Figure 4). This constancy, however, could be explained in another way [*Fredriksson*, 1963]. If the droplets were quenched, olivine would precipitate first, in a matter of seconds, and would have an almost constant composition. The residue may solidify as glass which may devitrify into plagioclase and orthopyroxene (usually formed below 1075°C) during subsequent slower cooling, possibly after

accumulation of the chondrules, or later reheating. The feasibility of such a process has been shown by *Fredriksson and Ringwood* [1963]. The varying composition of olivines and pyroxenes in Chainpur-type chondrites and in the ones listed in Table 8 may simply be due to somewhat slower cooling than in ordinary chondrules so that zonal structure could develop. This is substantiated by the unusually high Ca content in the Chainpur pyroxenes which indicates that this mineral had time to crystallize at higher temperatures, possibly directly from the melt.

If coexisting olivines and pyroxenes are compared with *Bowen and Schairer*'s [1935] data on the $MgO-FeO-SiO_2$ system, it appears that the $Fe/(Fe + Mg)$ ratios agree fairly well, although the olivine seems to be too rich in Mg (or the pyroxene in Fe). This seems consistent with a rapid crystallization, producing Mg-rich olivine and an Fe-enriched glass, later recrystallizing mainly to pyroxene and plagioclase. For the present qualitative discussion the 1550°C isothermal plane of *Bowen and Schairer*'s [1935] $MgO-FeO-SiO_2$ phase equilibrium diagram has been used. This is shown in Figure 15 with points plotted as follows: L_{s11} and H_{s11} show the MgO, FeO, and SiO_2 (recalculated to 100
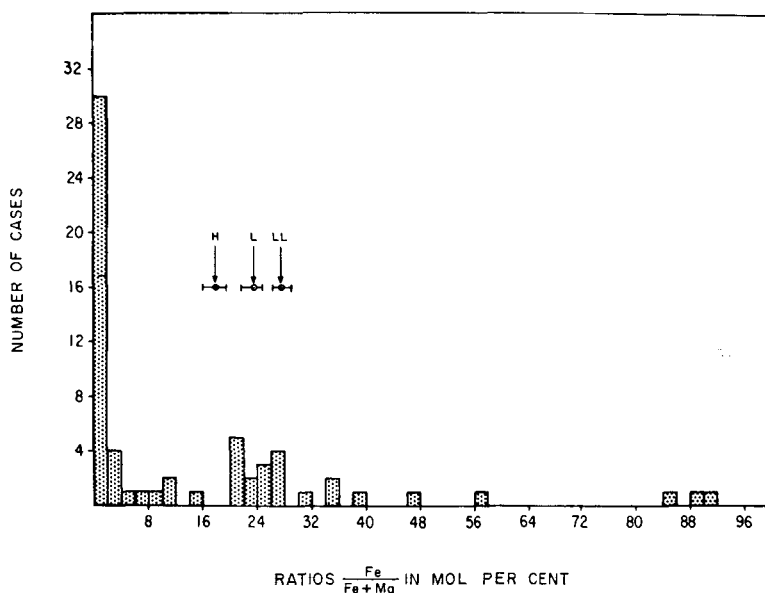

Fig. 14. Carbonaceous chondrite Murray. Frequency distribution of the mole per cent ratios Fe/(Fe + Mg) in 63 individual olivine crystals.

TABLE 8.　Chondrites Containing Olivines and Pyroxenes with Varying Composition

Name	Olivine Weight % Fe	Olivine Weight % Mg	Olivine Mole % Fe/(Fe + Mg)	Pyroxene Weight % Fe	Pyroxene Weight % Mg	Pyroxene Weight % Ca	Pyroxene Mole % Fe/(Fe + Mg)
Bishunpur	14.6	25.5	20.0	12.0	16.6	0.35	23.9
				14.9	14.9	0.35	30.3
Bremervörde	12.9	26.8	17.3	3.4–8.7	21.2–18.5	0.52–0.64	6.5–17.0
				8.4	18.6	0.74	16.4
				11.0	16.5	0.94	22.5
Castalia	13.3	26.2	18.1	6.3	20.6	0.14	11.8
	13.8	26.8	18.3	8.6	19.0	0.44	16.5
	15.6	25.5	21.0	10.4	17.7	0.39	20.4
Khohar	5.1	31.7	6.5	2.7	21.3	0.24	5.2
	14.3	26.3	19.1	8.9	18.6	0.55	17.2
	16.6	24.9	22.5	9.9	17.7	0.59	19.6
	17.6	24.2	24.0				
	18.2	23.9	24.9				
Lua	13.5	26.7	18.0	3.0	22.4	0.32	5.5
	15.0	25.9	20.1				
	16.0	25.3	21.6				
	16.8	25.0	22.6				
Mezö-Madras	11.7	27.6	15.6	9.2	18.7	0.10	17.7
	15.6	25.2	21.2	9.6	18.0	0.23	18.8
	15.7	24.8	21.6	13.8	11.9	0.80	33.6
	15.7	25.2	21.3				
	15.8	25.0	21.6				
	15.8	25.1	21.5				
	15.9	24.9	21.8				
	15.9	25.1	21.6				
	15.9	25.2	21.6				
	16.2	24.9	22.1				
	16.6	24.8	22.6				
	17.9	23.8	24.7				
	17.9	23.9	24.6				
	20.5	20.9	29.9				
Prairie Dog Creek	10.6	27.7	14.3	5.8–6.9	20.3–20.0	0.15	11.1–13.1
	13.1	26.3	17.8	6.1	20.2	0.44	11.6
	13.1	26.6	17.7	9.0	18.7	0.22	17.3
	13.2	26.0	18.1	14.1	15.1	0.47	28.9
	13.3	26.1	18.2				
	13.3	26.4	18.0				
	13.5	26.3	18.3				
	13.6	26.1	18.5				
	13.6	26.3	18.4				
	13.7	25.9	18.7				
Sindhri	4.6	31.3	6.0	1.9	23.0	0.19	3.5
	5.2	31.1	6.8	2.0	22.7	0.10	3.7
	9.7	28.9	12.8	2.9	21.8	0.20	5.5
	10.4–13.1	28.7–27.7	13.6–17.1	2.9	22.2	0.17	5.4
	10.6	28.5	13.9	3.5	21.0	0.20	6.8
	11.2	28.0	15.0	4.7	21.2	0.20	8.8
	11.4	28.2	15.0	5.3	21.3	0.10	9.8
	11.8	27.9	15.6	5.8	20.5	0.29	11.0
	11.9	27.6	15.8	6.5	20.3	0.28	12.2

TABLE 8. (Continued)

| | Olivine | | | Pyroxene | | | |
| | Weight % | | Mole % $Fe/(Fe + Mg)$ | Weight % | | | Mole % $Fe/(Fe + Mg)$ |
Name	Fe	Mg		Fe	Mg	Ca	
	12.2	27.3	16.3	7.6	19.4	0.10	14.6
	12.8	27.0	17.1	8.4	18.9	0.38	16.2
	13.2	26.8	17.7	8.4	19.0	0.44	16.1
	13.3	26.4	18.0	8.4	19.2	0.36	16.0
	13.3	26.4	18.0	8.5	18.8	0.51	16.5
	13.3	26.7	17.8	8.5	19.0	0.47	16.3
	13.3	26.9	17.7	9.1	18.5	0.38	17.6
	13.3	27.3	17.5	10.4	17.9	0.16	20.2
	13.3	27.6	17.3	12.2	16.9	0.75	23.9
	13.6	27.1	17.9				
	13.7	26.9	18.2				
	13.7	27.2	18.0				
	13.8	26.8	18.3				
	13.8	26.8	18.3				
	13.9	26.6	18.5				
	14.2	26.9	18.7				
	14.6	26.5	19.3				
	15.2	26.0	20.3				
	15.2	26.0	20.3				

per cent) for the average L- and H-group chondrites; L_{tot} and H_{tot} were obtained by calculating the total iron (including Fe in metal and troilite) as FeO, thus assuming that all iron was once oxidized; similarly, O_{tot} indicates the composition of the Orgueil carbonaceous chondrite. These values are based on the data given by *Urey and Craig* [1953]. Finally, L_{ol} and H_{ol} show the composition of the average olivine compositions for L- and H-group chondrites as given in Table 4. It is immediately apparent that melts of L_{s11} or H_{s11} composition could hardly precipitate olivine of the observed composition. However, partial reduction of a melt of composition H_{tot} (or O_{tot}) may yield L- and H-group chondrites with the proper olivines and proper amounts of metallic nickel-iron. If, for example, metallic nickel-iron would segregate by reduction from a silicate melt of composition H_{tot} but not be removed from the system, a point on the H_{tot}-H_{s11} line would be reached where H-group olivine could precipitate, leaving the bulk composition within the H-group range. If from the same melt (H_{tot}) some of the segregated metallic nickel-iron is removed, a composition could be reached where L-group olivine could precipitate and the total melt reach the

L_{tot} point. Apparently more ferrous iron than is now observed was present during the formation of the meteoritic olivines, part of which is now observed as metallic nickel-iron. It is also clear that some further reduction must have occurred during or after the chondrule formation as *Ringwood* [1961] suggested. Presence of a metallic iron phase during the silicate formation is further indicated by the low Ni content of the chondritic olivines (see paragraph *b* below). *Urey and Mayeda* [1959] suggested that metallic nickel-iron in chondrites could have been introduced mechanically. They thought that the occurrence of kamacite, taenite, plessite, and the morphology of the metal particles could best be accounted for by assuming the grains to be fragments of slowly cooled 'primary bodies' which have been mixed with the silicate portion subsequent to the chondrule formation to give the 'secondary bodies.' The main argument for this proposal seems to be that the metallic particles in chondrites apparently cooled slowly. This can be accounted for, however, even if chondrules, metal, and interstitial matter solidified rapidly, by assuming that the chondrites remained at more moderate temperatures (e.g., 500°C to 700°C [*Urey and Mayeda,*
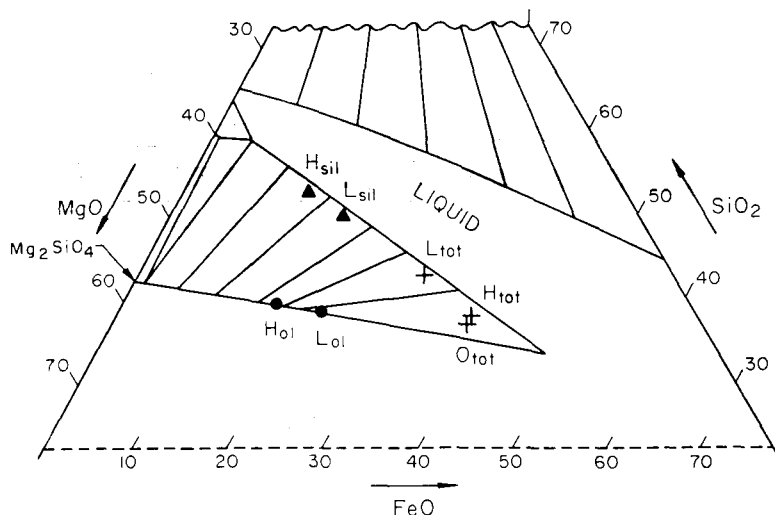
Fig. 15. Phase relations of 1550°C in the MgO-FeO-SiO₂ system after *Bowen and Schairer* [1935]. L_{sil} and H_{sil} show average MgO, FeO, and SiO₂ for L- and H-group chondrites; H_{tot} and L_{tot} were calculated from these values by adding FeO corresponding to average metallic Fe contents; O_{tot} represents the carbonaceous chondrite Orgueil. H_{ol} and L_{ol} indicates average olivine compositions. The figure illustrates that more ferrous iron than is now in the silicates was present during olivine crystallization. Note also that from H_{tot} to H_{sil} the melting point remains practically constant $\gtrsim$1550°C, for example, above the melting point of nickel-iron.

1959]) after agglomeration for a longer period of time, for example, simultaneously with the recrystallization of the glass to pyroxene and plagioclase. Besides the results discussed above, however, several other observations indicate that the metallic nickel-iron was formed from the same melt as the silicates. Several of these observations are listed below, some of which have already been discussed by *Ringwood* [1961] and *Urey* [1964].

a. Fredriksson [1963] showed that some chondrules of the Bjurböle chondrite contain as much nickel-iron as the matrix. Microscopic estimates indicate that this is the case also in other chondrites. The apparently larger size of the metal particles in the matrix may be due to later recrystallization [*Fredriksson*, 1963]. The metallic particles inside the chondrules obviously constitute a coexisting phase and can hardly be explained by a mechanical mixing of solid particles after chondrule formation.

b. The amount of metallic nickel-iron stays within characteristic ranges in LL-, L-, and H-group chondrites (LL group, 1.72 to 3.23; L group, 4.40 to 11.65; H group, 14.17 to 19.81, in weight per cent [*Keil*, 1962a, b]). This fact

indicates a close genetic relationship between metal and silicate (as do the previously discussed phase relations).

c. The amount of Ni in chondritic olivine[6] is considerably lower than in most terrestrial olivines. Meteoritic olivine should contain higher amounts than observed unless the nickel was scavenged by metallic iron during the formation of the chondritic silicates as is the case for many chondrules (see paragraph *a* above). Consequently, it seems likely that the olivine in the matrix of the chondrites is also formed in the presence of molten metal.

d. The irregular shape of the nickel-iron grains in chondrules is apparently due to the fact that the metal solidified last (together with troilite), when only small interstitial spaces were left between the largely solidified silicates, rather

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[6] Recent microprobe analyses by Fredriksson (unpublished) show maximum Ni contents of 120–200 ppm Ni in olivine from Bjurböle (L group) and approximately 100 ppm in Assisi (H group). The pyroxenes in both chondrites seem to contain less nickel. The Marjalahti olivine (used as iron standard) contained between 50 and 150 ppm Ni, which agrees with the analyses quoted by *Mason* [1962b] for pallasites.

than due to fragmentation of solid nickel-iron and mixing with silicates. The occasionally observed fragmentation and distortion of nickel-iron grains ('veins' cutting iron grains into fragments [e.g., *Urey and Mayeda*, 1959, Figure 8e]) can be explained by mechanical shock deformation in situ [*Fredriksson et al.*, 1963].

The present investigation indicates that ordinary chondrites are nonequilibrium, cogenetic assemblages of silicates, mainly olivine and pyroxene, and metal. These results, together with other existing evidence, permit the assumption that L- and H-group chondrites could have originated from the same parent material (in one or several parent bodies). Consequently, this study supports a model for the origin of chondrites as proposed by *Fredriksson* [1963], a modification of the ideas presented by *Ringwood* [1961].

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